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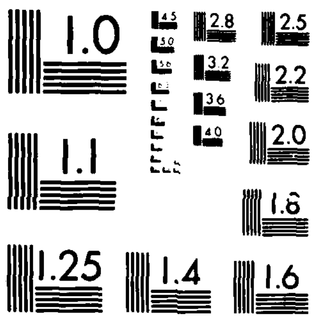

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Mechanics and Materials Center
TEXAS A&M UNIVERSITY
College Station, Texas

RESIDUAL-STRESS INDUCED DAMAGE

IN COMPOSITE MATERIALS

Annual Technical Report

by

Y. Weitsman

CIVIL ENGINEERING DEPARTMENT
TEXAS A&M UNIVERSITY

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For the period

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Submitted to the

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Principal Investigator: Y. Weitsman

Mechanics and Materials Center

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College Station, Texas 77843

April 1985

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1. Summary

Research up-to-date included experimental and analytical aspects.

The experimental task involved several unidirectional and cross-ply lay-ups of AS4/3502 graphite/epoxy composite coupons. Those samples were exposed to various excursions of temperature and moisture, and damage was inspected and recorded under all circumstances.

In the case of cross-ply samples it was noted that under sharp temperature fluctuations the damage was severe but generally more dispersed, while under gradual thermal excursions the damage was milder but of a denser distribution.

No damage due to temperature fluctuations was noticed in unidirectional coupons.

In the case of moisture, it was observed that damage in the form of fiber/matrix debondings grew under repeated exposures to dry and humid ambient environments. The damage was essentially of the same form in both uni-directional and cross-ply coupons.

Two analytical approaches were formulated to represent the abovementioned damage forms.

The first approach considered a "representative cell", which contains a single trasverse crack across the 90° ply, with the purpose of relating the fracture energy to the dimensions of that cell and to the temperature amplitude.

The second approach employed damage as a continuously dispersed parameter, or "internal state variable". The purpose of this approach was to model damage and express damage-growth laws with special emphasis on the effects of temperature and moisture.

2. Research Objectives

The main objective of this research is to evaluate the role of temperature and moisture as damage inducing agents in composites.

This objective is to be achieved by subjecting composite coupons to several excursions of temperature and humidity, with variations in both amplitudes and rates, and inspecting the resulting damage.

Furthermore, the formation and growth of damage are to be modelled analytically in order to relate them to material properties and ambient environmental conditions. [illegible]

3. Status of Research - Experimental

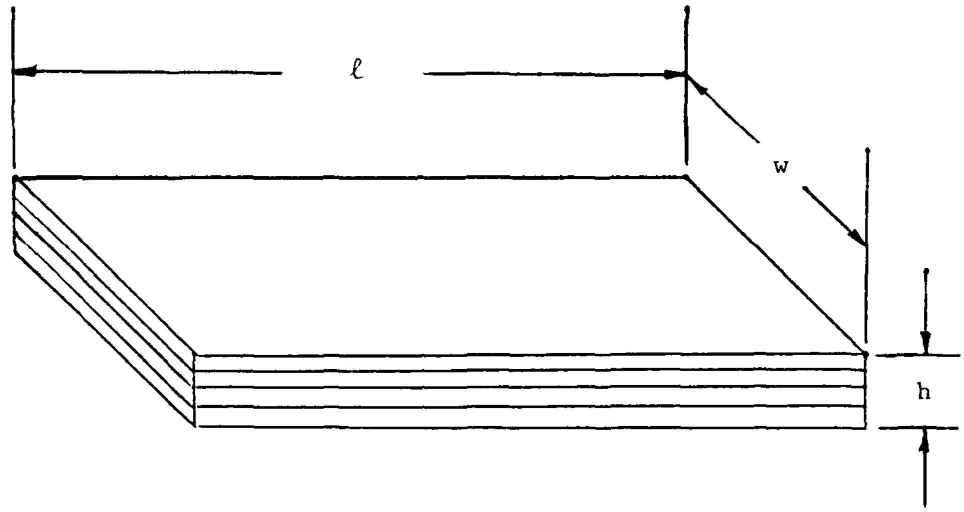
All experiments involved AS4/3502 graphite/epoxy composites.

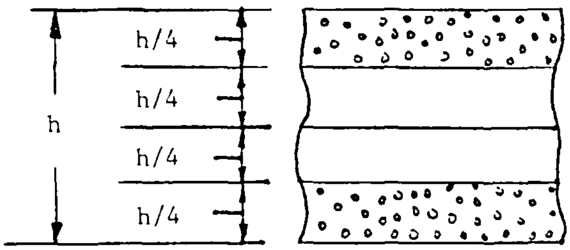
3.1. Thermal Excursion Experiments

Several groups of coupons, of lay-up and dimension as shown in Fig. 1., were cured according to manufacturer's specifications at 350° F and cooled down gradually to room temperature, of 75° F. Damage in the form of transverse cracking was observed at room temperature. Subsequently, a portion of the coupons were cooled abruptly to -320° F, undergoing a "shock" thermal drop ($S\Delta T$), within about 6.6 seconds. Additional sub-groups were gradually re-heated to 200° F and 400° F, respectively, then shock-cooled to -320° F.

The experimental scheme is summarized in Table 1, where typical damage forms are also listed. Some of these forms are illustrated in Figs. 2 and 3. Note that although in all cases the total temperature drop is of an identical amplitude T = -720° F, the variations in the portion of the abrupt drop, $S\Delta T$, betwen 400° F and 720° F resulted in substantially different crack geometries. In the case of $(0_4/90_4)_S$ lay-up, the spacing

TYPICAL SPECIMEN GEOMETRY





TYPICAL CROSS-PLY
PLY THICKNESS

Ply Sequence AS4-3502	ℓ (mm)	w (mm)	h (mm)
0°_{12}, 90°_{12}	6.25 ± 1.5	18.5 ± 1.0mm	1.65 ± 0.05mm
$(0^\circ_4, 90^\circ_4)_s, (90^\circ_4, 0^\circ_4)_s$	6.25 ± 1.5	18.5 ± 1.0mm	2.05 ± 0.05mm

FIGURE 1

COOL CYCLE

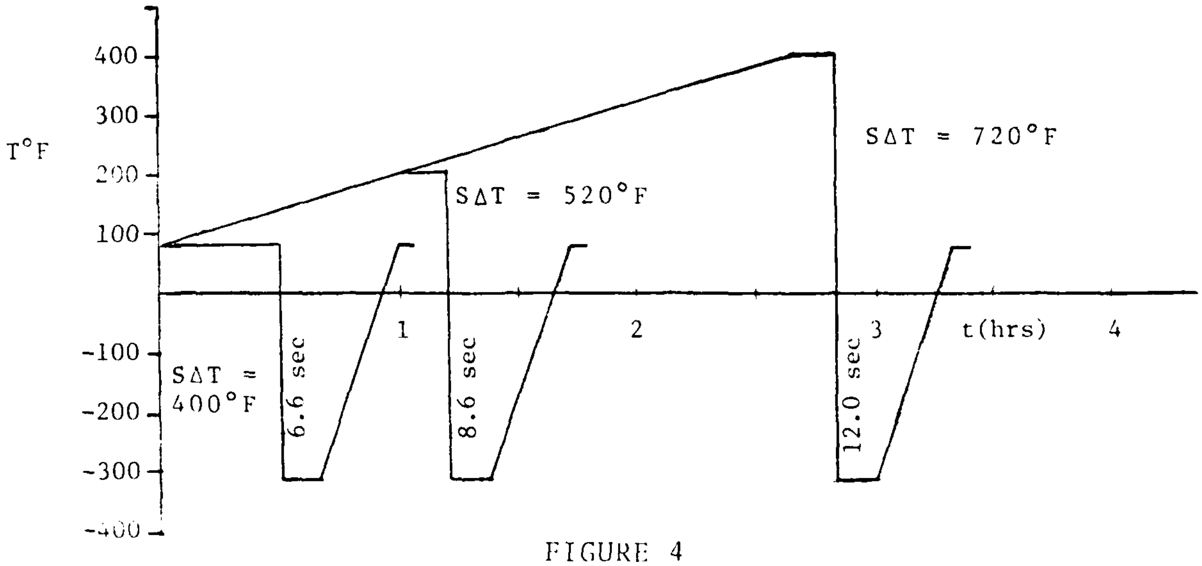
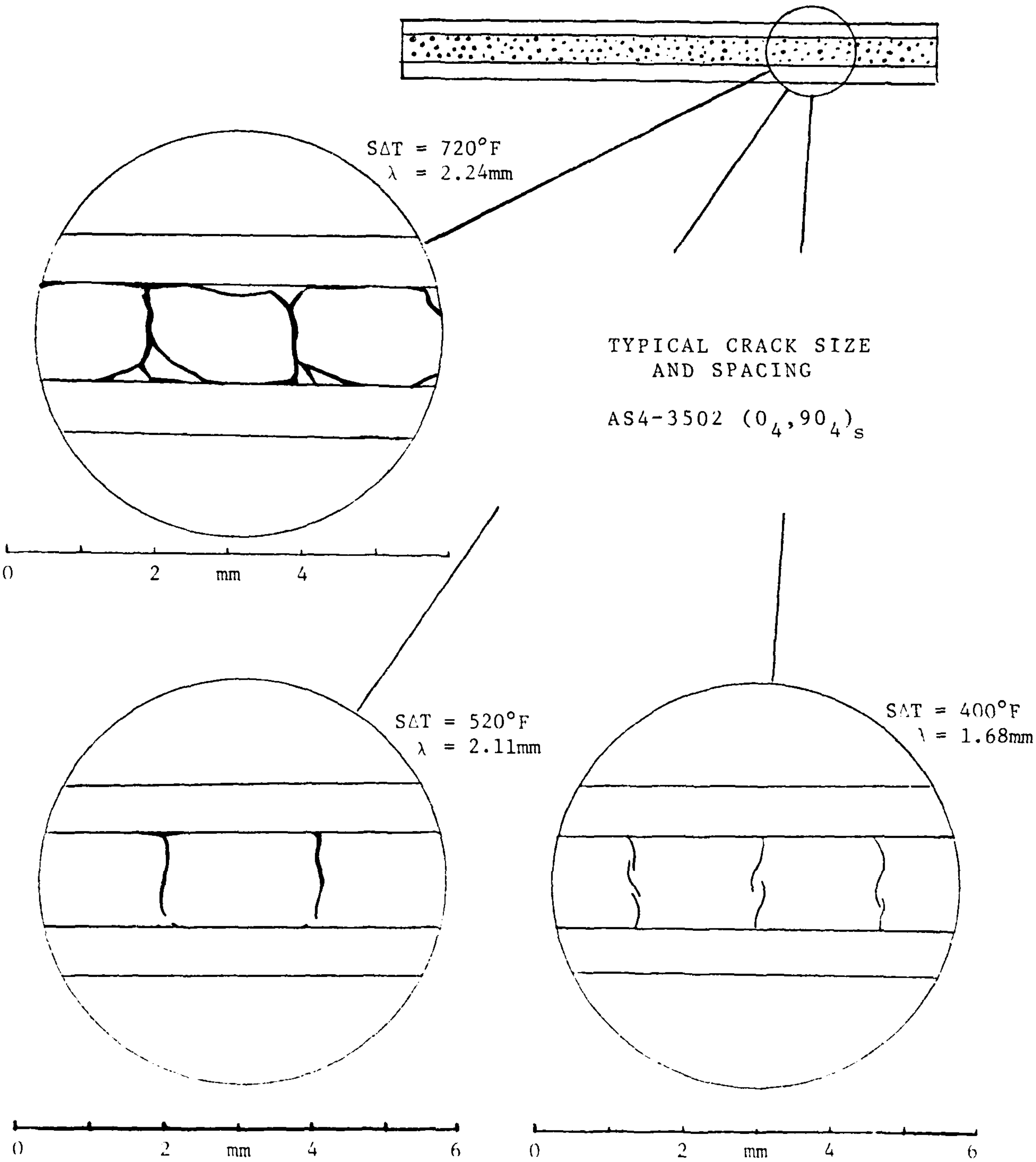


FIGURE 4

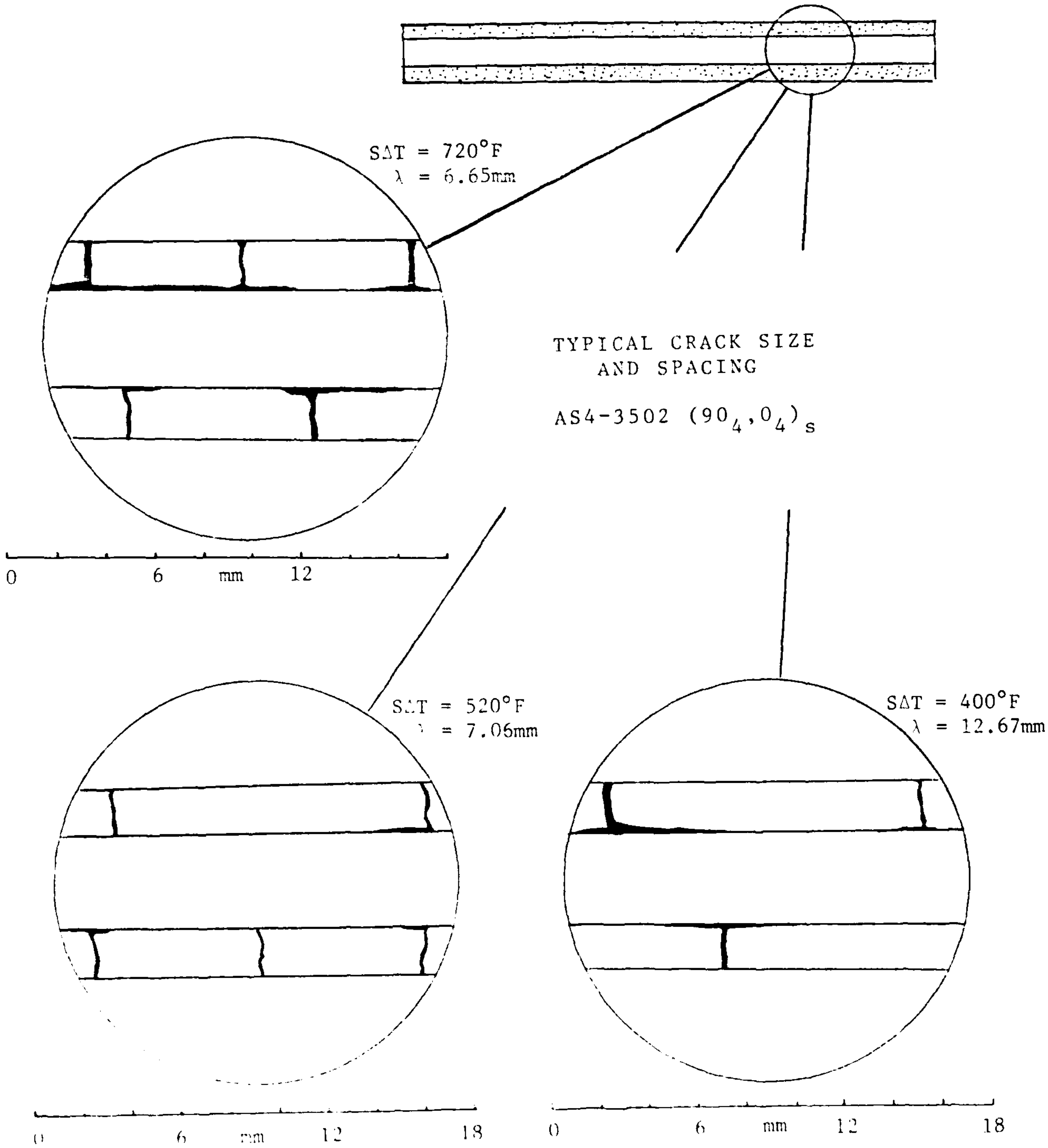
Ply Sequence AS4-3502	SΔT°F	ΔT°F	Theo. ΔT°F for FPF	Description of observed damage and typical crack spacing λ
0°_{12}	720	720	—	No cracking, w/ or w/out pre-notch
90°_{12}	720	720	—	No cracking, w/ or w/out pre-notch
$(0^{\circ}_{4}/90^{\circ}_{4})_{s}$	720	720	398	Very wide, branching cracks, completely transverse 90° plies, much delamination, λ = 2.22mm
$(0^{\circ}_{4}/90^{\circ}_{4})_{s}$	520	720	398	Medium to wide, unbranched cracks, most transverse 90% of 90° plies, occasional delamination, λ = 1.68mm
$(90^{\circ}_{4}/0^{\circ}_{4})_{s}$	400	720	398	Thin to medium, discontinuous cracks, crack groups completely transverse 90° plies, no delamination, λ = 1.68mm
$(90^{\circ}_{4}/0^{\circ}_{4})_{s}$	720	720	398	Very wide, completely transverse 90° plies, much and very long delamination, λ = 6.65mm
$(90^{\circ}_{4}/0^{\circ}_{4})_{s}$	520	720	398	Medium to wide, completely transverse 90° plies, some delamination, widely varied λ, λ = 7.06mm
$(90^{\circ}_{4}/0^{\circ}_{4})_{s}$	400	720	398	Very wide, completely transverse 90° plies, delamination at almost all cracks, λ = 12.67mm

TABLE 1



SΔT = 720°F
λ = 2.24mm
TYPICAL CRACK SIZE
AND SPACING
AS4-3502 (0₄,90₄)s
0
2
mm
4
SΔT = 520°F
λ = 2.11mm
SΔT = 400°F
λ = 1.68mm
0
2
mm
4
6
0
2
mm
4
6

FIGURE 2



SΔT = 720°F
λ = 6.65mm
TYPICAL CRACK SIZE
AND SPACING
AS4-3502 $(90_4,0_4)_s$
0
6
mm
12
SΔT = 520°F
λ = 7.06mm
SΔT = 400°F
λ = 12.67mm
0
6
mm
12
18
0
6
mm
12
18

FIGURE 3

between veritcal cracks increased with S\T, as did the severity of the damage. In addition, longitudinal cracks appeared in the outer ply-group of 0°. For a "controlled" $(0_4/90_4)_S$) lay-up, that was gradually cooled-down to room temperature, no delaminations were associated with either transverse or longitudinal cracks.

Similar experiments were performed on uni-directional composite coupons, with cracks and notches of various shapes and depths etched into their surfaces. No damage was observed in those coupons under any of the abovementioned thermal excursions. It was therefore concluded that fracturing due to temperature occurs at the ply level, due to laminate residual stress, and not at the micro level which would be due to fiber/matrix mismatch.

3.2 Moisture Excursion Experiments

Uni-directional coupons were manufactured according to specifications and exposed to 95% R.H. at 163° F in custom made environmental chambers.

Weight-gain was monitored up to saturation, at which time inspection under the scanning electron microscope revealed no damage.

Simultaneously, groups of coupons were placed alternately, every twelve days, in dry and humid chambers. Damage was inspected after eight complete cycles, i.e. 192 days, under SEM. It was noted that many micro cracks developed along the fiber/matrix interfaces, while some micro cracks coalesced to form long continuous cracks. Typical details are shown in Figs.4-8.

Therefore, moisture, induces damage on the micro scale, in contrast with an earlier observation of temperature effects.

4. Status of Research - Analytical

4.1 Energy Release-Rate Calculations

Figure 4. Individual debondings at the fiber-matrix interfaces in a 12-ply uni-directional, AS4/3502 gr/ep laminate. Laminate was subjected to eight full cycles of wet/dry exposures at 95% R.H. and 0% RH at 12 day/12 day intervals. T = 163°F.

Micrograph from the vicinity of the free surface.

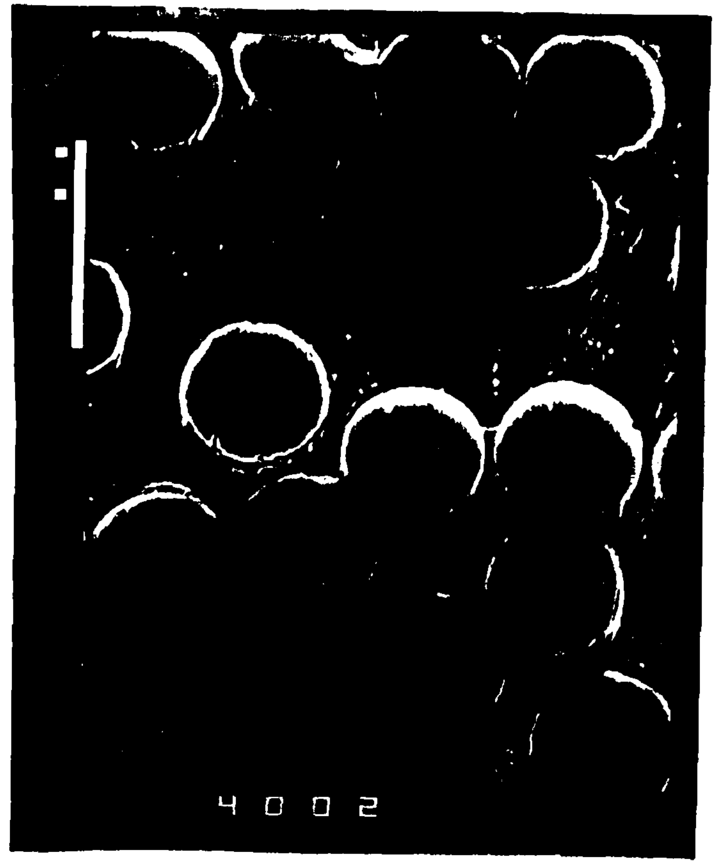


Figure 5. Coalescence of interfacial debondings in the laminate subjected to the same conditions as listed in Fig. 4.

Micrograph from the vicinity of the free surface.

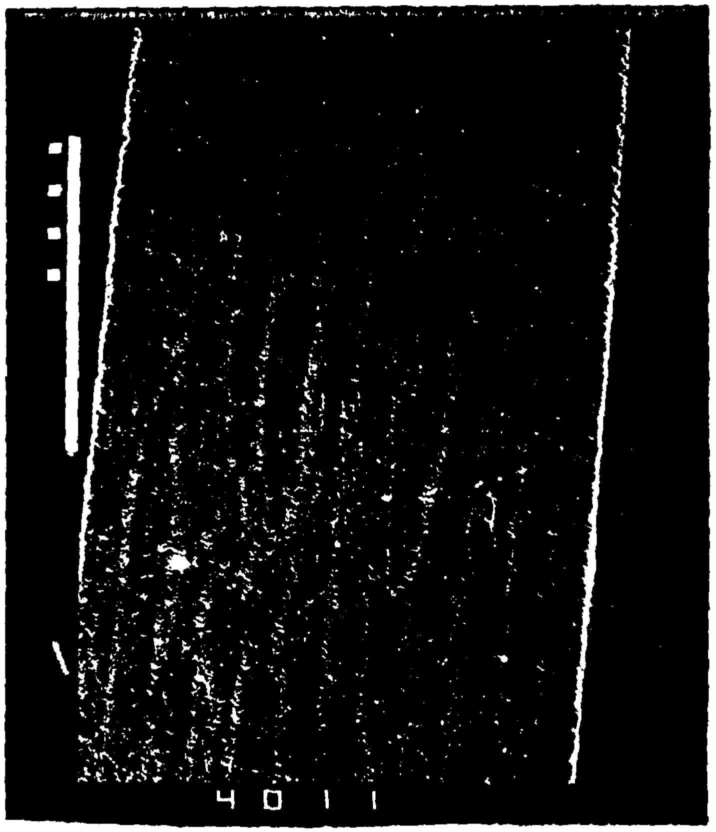


Figure 6. Overall view of a branched major crack in the laminate subjected to the same conditions as listed in Fig. 4.

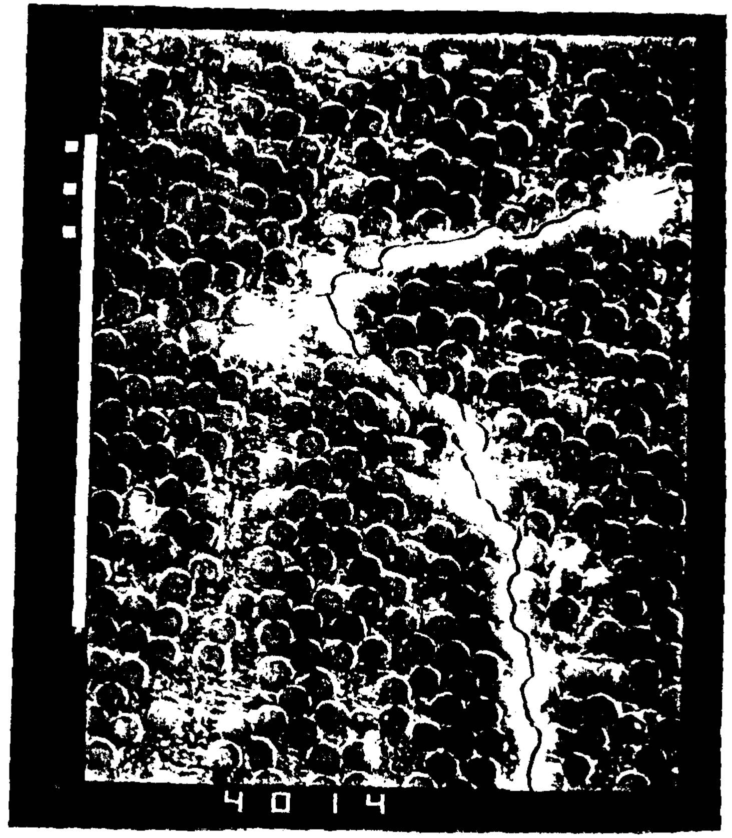


Fig. 7. Magnified details of the branched crack shown in Fig. 6.

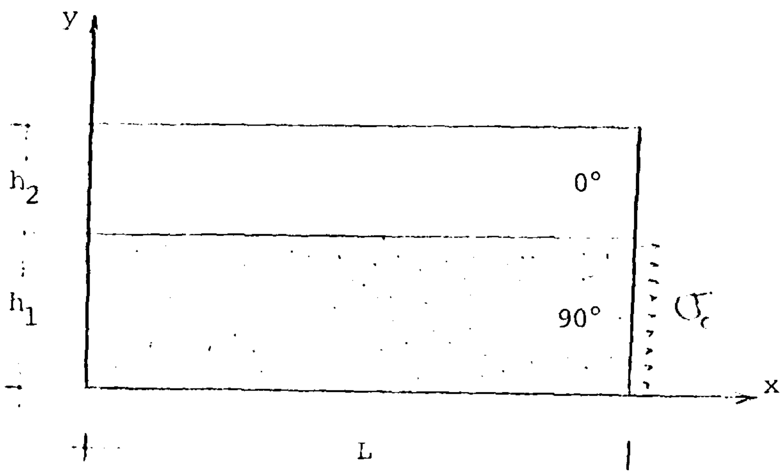


Figure 9. The representative cell for computation of energy release rates in thermally conditioned coupons. The stress σ_o is the residual thermal stress in an uncracked coupon.

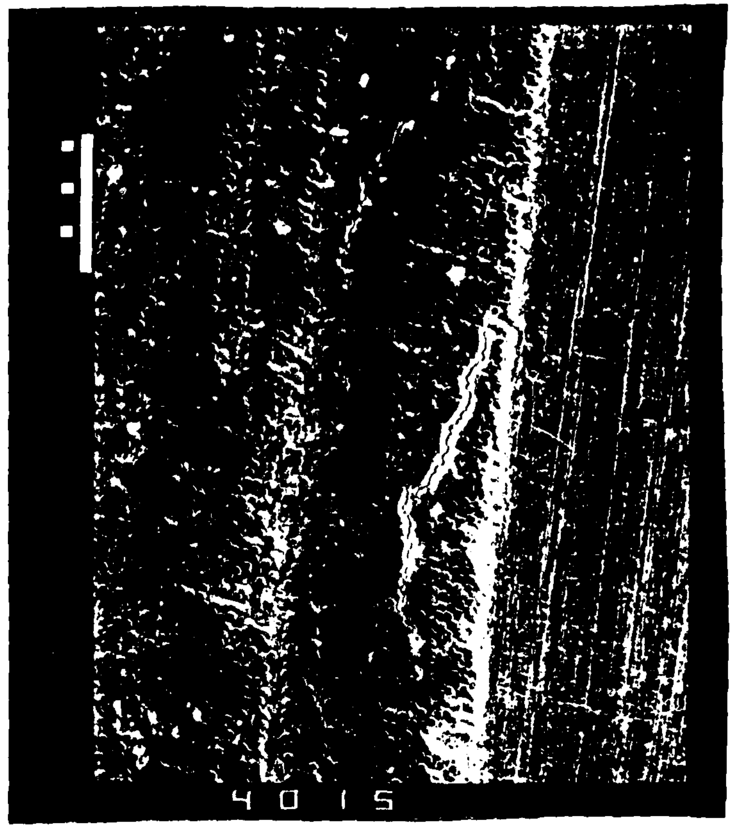


Figure 8. Two major horizontal cracks in the laminate subjected to the same conditions as listed in Fig. 4.

Consideration was given to a representative cell shown in Fig. 9. The length L of this cell is half the crack spacing, and its height is half the laminate thickness. Let the cell be subjected to a traction σ_o, of magnitude equal to the residual thermal stress in an uncracked laminate.

The computation of energy release rate when fracture occurs due to residual stresses involves several steps.

The first step consists of solving the boundary value problem for the cell shown in Fig. 9, as follows:

$$\tau_{xy}(0,y) = u(0,y) = 0$$

$$\tau_{xy}(x,0) = v(x,0) = 0$$

$$\tau_{xy}(x,h_1+h_2) = \sigma_y(x,h_1+h_2) = 0$$

$$\tau_{xy}(L,y) = 0$$

$$\sigma_x(L,y) = \sigma_o \qquad 0 < y < h_1$$

$$u(L,y) = 0 \qquad h_1 < y < h_2$$

In addition, the appropriate stress-strain relations should be employed for layers "1" and "2".

Approximate solutions can be obtained by means of variational techniques using kinematically admissible fields. Several such fields were utilized, some of which considered inflexible layers and others that allowed for bending effects. For future reference, denote the strain energy density associated with the solution to the above problem by w_a.

The second step involves the calculation of the strain energy density in an uncrached laminate due to residual thermal stresses. Denote this quantity by w_o.

In the third step the quantities w_a and w_o are combined to provide the strain energy density of the cracked laminate $w_c = w_o+w_a$.

Next, the total energy of the cracked laminate is obtained according to

$$W_c = \int_V w_c dv$$

and compared against the total energy in the uncracked laminate, namely

$$W_o = \int_V w_o dv$$

Finally $(W_c - W_o)$ should equal $-G_c h_1$, where G_c is the critical energy release rate for transverse cracking. In AS4/3502 G_c is about 0.8-1.0/ in-lb./in^2.

Preliminary computations indicate that a simple, kinematically admissible field presentation for the problem shown in Fig. 9 corresponds to G_c of about only 0.2 in.-lb./in^2 and that the incorporation of bending into the model would raise the value of G_c by only a few percent.

It was therefore attempted to account for the energy release rate associated with the longitudinal cracks in the outer 0° plies. When this additional energy release rate was computed separately from its transverse counterpart, then the two quantities together amounted to $G_c^{\text{total}} = 0.5$ lb-in/in^2.

It therefore appears that the complex fracture patterns which develop due to cool-down cannot be handled by approximate, kinematically admissible fields and may require the employment of mixed variational methods, like those based on Reissner's principle and developed by Pagano. Alternately, other types of coupons, perhaps involving aluminum claddings should be tested.

Furthermore, it is not clear at this time why should an increase in the rate of cooling cause the noticeable difference in damage forms that were shown in Figs. 2 and 3.

4.2 Damage-Parameter Modelling

A formulation of constitutive relations, derived from basic principles of continuum mechanics and thermodynamics, was undertaken. The formulation considered strains, temperature, moisture, temperature and moisture gradients as well as "damage" as internal state variables. In particular "damage" was conceived as a measure of internal fractured surfaces. Since mathematically such internal areas are cross products of two vectors, the damage d was represented by an axial vector or, alternately, a skew symmetric tensor.

Although many details still remain to be completed and verified, the main features of the resulting expression can be stated as follows:

- The internal free energy ψ has the form $\psi = \psi(E_{ij}, D_{ij}, m, T)$ where E and D are strain and damage tensors (in material coordinates) and m,T denote moisture and temperature, respectively.
- The stress tensor σ_{ij} is derived from $\frac{\partial\psi}{\partial E_{ij}}$ and thereby depends also on E_{ij}, D_{ij}, M and T as before. It follows that the constitutive relations involve parameters which depend on D, m, and T even in the linear case.
- Moisture and temperature diffusion are coupled, and diffusivities depend in general on strain, or stress, amplitudes.
- Damage growth, $\dot{d}_{ij}$, depends not only on E_{ij}, D_{ij}, m, and T as before but also on the gradients of both moisture and temperature.

The last conclusion, which was derived from a strictly formal procedure, seems to be confirmed by observations of damage under various fluctuations of moisture and temperature. It therefore appears that the model contains the proper set of variables to accommodate the experimental observations, although the exact form of the constitutive relation is not yet known.

5. List of Professional Personnel

Dr. Y. Weitsman, Professor of Civil Engineering, Principal Investigator.

Mr. L. Clark, a Ph.D. Student at the Aerospace Engineering Department, was employed as a research assistant from 1 Feb. 1984 to 31 Aug. 1984, when employment was terminated.

Mr. G.-P. Fang, an M.Sc. student at the Aerospace Engineering Department, has been employed as a research assistant from 1 Sept. 1984 to the present time.

6. Interactions

During the report period Dr. Weitsman attended the following meetings:

-The April Meeting of ASTM in Philadelphia (April 1-6, 1984).

-The 21st Annual Meeting of the Society of Engineering Science in Blacksburg, VA (Oct. 16, 1984) where he presented a paper on "Crazing in Polymers".

-The Mechanics of Composites Review Meeting in Dayton, Ohio (Oct. 17), where he presented a talk on "Damage Mechanisms and Moisture Effects in Composites and Polymers."

-The 17th IUTAM International Congress of Applied Mechanics in Copenhagen, Denmark (Aug. 17-25, 1984).

In addition, Dr. Weitsman conferred with researchers at Harvard, Brown and Michigan State Universities and consulted with Shell Development Co.

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